

The onset of landscapes in the Balearic Islands: A study-case of Addaia (northern Minorca, Spain)

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ARTICLE INFO

Keywords:

Palynology
Multi-proxy
Mediterranean
Climate change
Land-use
Resilience

ABSTRACT

Paleoenvironmental and archaeological data show that Mediterranean landscapes result from long-term socio-environmental interactions. Mediterranean islands constitute a place of passage where the creation of cultural landscapes can be traced through colonization and anthropization histories. Palynological studies carried out in the Balearic Islands highlight a deep vegetation change from the mid- to late-Holocene, but the climate-environmental-human interactions are not fully understood yet. In this study, we aim to disentangle the causalities of landscape changes during the last six millennia using a multi-proxy approach on an off-site core for the first time in Minorca island. We find that, during the mid-Holocene, the climate was wetter than today with less rainfall seasonality than in the current Mediterranean. This climate, favoured the expansion of box formations and the predominance of forested formations with minimal anthropized conditions. First agropastoral activities appeared in the sequence between ca. 3500–2650 cal BCE in north-eastern Minorca, coinciding with other sporadic archaeological evidence (Cova dels Morts rock-shelter) which support the possibility of a pre-Chalcolithic discovery and frequentation of the island. We record deep environmental change during the third millennium cal BCE, reflected in the substitution of the former mesophytic vegetation by Mediterranean maquis formations dominated by wild olive trees, heathers, mastic and Cistaceae. We propose that maquis, garrigues and open-land vegetation were favoured by human action in a context of increasing climatic dryness and seasonality, promoting vegetation flammability and substitution of former mesic communities to more adapted thermophilous vegetation. The comparison of our new record from Addaia with other pollen studies from the Balearic Islands highlights the resilience of mesic vegetation to climate change. This is shown by the survival of box formations to the increased aridification initiated at ca. sixth–fifth millennium cal BCE (ca. 7–6 cal kyr BP) in the Western Mediterranean which culminated at ca. fourth–third millennium cal BCE (ca. 5–4 cal kyr BP). Additionally, whilst sporadic human presence versus stable occupation are difficult to detect in archaeological records, the coupling with paleoenvironmental studies may offer new scenarios and information for human arrival in the Balearic Islands.

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1. Introduction

The Mediterranean Basin constitutes a good example of a “place of passage”, and the Balearic Islands are not an exception. Therefore, insularity cannot be considered as physical and environmental conditions that directly explain cultural evolution as have been formerly interpreted by determinist approaches (Knapp, 2007). Numerous island archaeological and paleoenvironmental studies have based their epistemological approaches on the idea of “islands as laboratories for the study of cultural evolution”, influenced by the seminal work of Evans (1973). Nevertheless, it seems clear that the history of islanders is one of movement and connectivity (Knapp, 2007), which led to the creation of islandscapes (Broodbank, 2000). This concept implies a more flexible paradigm that integrates island landscapes and seascapes which allow us to understand the complex human-nature interactions in the frame of connectivity with the mainland and other islands. To take even further the idea that islands allow an all-round connectivity (Horden and Purcell, 2012), the concept aquapelasgos (Hayward, 2012; Dawson, 2012) puts the emphasis in the possibilities of connection that archipelagos allow. Such approach should be related to the notion of cultural landscape in which landscapes are lands transformed by human activities which replace natural ecosystems (Mercuri, 2014). Insularity should not be seen as a geographical isolation, but rather as a dynamic interaction between islanders and their physical environment, and their relationship with the outsiders (Rainbird, 1999; Knapp, 2008; Broodbank, 2000; Rainbird, 1999; Frieman, 2008). Nevertheless, Mediterranean islands constitute fragile environments prone to record

the effects of human occupation and climate variability. Paleoenvironmental studies have proved to be a suitable approach to generate new scenarios for human arrival on islands, as has been proved in the Oceanic islands and the Azores archipelago (Rull et al., 2017; Prebble and Wilmshurst, 2010). In this context, it is necessary to understand the history of such environments and the causalities of landscape changes.

Paleoenvironmental and archaeological data have revealed that Mediterranean landscapes result from complex long-term socio-environmental interactions (Mercuri et al., 2011; Roberts et al., 2001, 2011; Walsh, 2014), as environmental changes and social dynamics are co-evolutionary processes (Dearing et al., 2006). In the last decades, there have been several paleoenvironmental studies in the Mediterranean islands that have revealed long human-environment interactions during the Holocene (e.g., Beffa et al., 2015; Tinner et al., 2009, 2016; Sadori et al., 2013; Burjachs et al., 2016a; Yll et al., 1997; Pérez-Obiol et al., 2000; Currás et al., 2017; Di Rita and Melis, 2013; Carroll et al., 2012; Djamali et al., 2013). Palynological studies carried out in the Gymnesics (Mallorca and Minorca) highlight an abrupt vegetation change at ca. 3200–3000 cal BCE in Mallorca (Burjachs et al., 2016a, 2016b) and between ca. 3650–2700 cal BCE in Minorca (Burjachs, 2006; Burjachs et al., 2016a, 2016b; Yll et al., 1997, 1999; Pérez-Obiol et al., 2000). During this change, the plant landscape dominated by *Juniperus*, *Corylus*, deciduous *Quercus* and *Buxus* was replaced by thermophilous communities formed by *Olea*, *Quercus ilex*-t, *Pistacia* and *Erica* in a short lapse of time. These vegetal communities have prevailed in the Gymnesics during the last five/four millennia (Yll et al., 1999). Such environmental change has been explained by drier climate

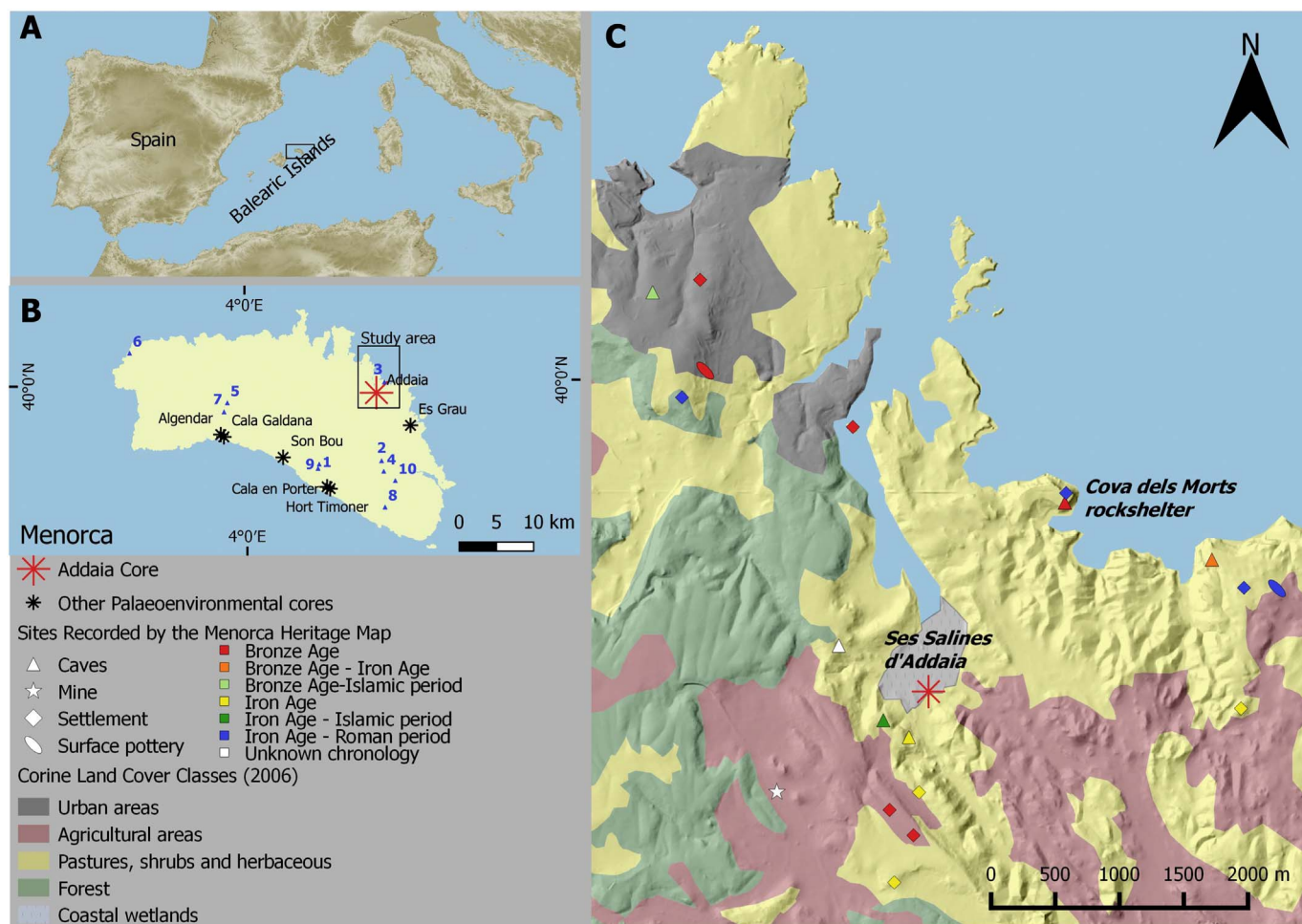


Fig. 1. Map showing the location of Addaia. A) Location of Minorca island within the Western Mediterranean; B) Minorcan pollen sequences and archaeological sites cited in the text: 1 - Ses Roques Llises, 2 - Biniai Nou, 3 - Cova dels Morts, 4 - Talatí de Dalt, 5 - Pas d'en Revull, 6 - Cova des Mussol, 7 - Cova des Càrritx, 8 - Biniparratx Petit, 9 - Torre d'en Galmés, 10 - Cornia Nou. C) Location of the drilling in relation to the main vegetation features and land uses and the microregional archaeological context.

conditions and a trend towards low rainfall and seasonality (Pérez-Obiol et al., 2000; Burjachs et al., 2016a), while human impacts have barely been considered. However, the different chronologies in the studied sites of both Minorca and Mallorca islands suggests that this environmental change can be interpreted on the basis of a complex interaction between vegetation dynamics, climate and human impact. To disentangle the causality of such deep landscape change, reliable age-depth models, multi-proxy studies and multidisciplinary works are required from now on.

In this paper we propose the study of socioenvironmental interactions from prehistory to the present based on the study of a new sequence located in North-Eastern Minorca in order to determine the role of humans and climate forcing on landscape change since the mid-Holocene, paying attention to how newcomers could have generated new landscape forms.

1.1. Geographical setting

Minorca is the northernmost island of the Mediterranean Balearic Archipelago (Fig. 1). It is a small island with a surface of 716 km². In Minorca, the northern region (*Tramuntana*) is formed by limestone and siliceous bedrocks from Palaeozoic and Mesozoic while the southern part (*Mitjorn*) region is a platform formed by Tertiary limestone bedrock eroded by deep ravines (Bourrouilh, 1983; Fornós and Segura, 2003). The Port d'Addaia constitutes a contact zone between these two geological regions (Pons and Gómez-Pujol, 2003). Minorca has a Mediterranean climate, characterized by seasonal and windy regime with a four-month-long summer drought (Gil and Olcina, 2001; Pons and Gómez-Pujol, 2003). The mean annual temperature ranges from 16 to 18 °C and the mean annual precipitation near the coring site is 570 mm, but rainfall distribution is rather irregular throughout the year, recording most of the precipitation during autumn and winter, including convection rainfall in late summer (Franquesa i Balcells et al., 2011; Guijarro, 1986).

Holm-oak woods of *Quercus ilex* L. (*Cyclamini balearici-Quercetum ilicis* O. Bolòs) constitute the potential vegetation in the deeper soils and the inner part of the island recording higher precipitations. Human activities have perturbed and even destroyed part of these woods, promoting degradation and the penetration of heliophilous species such as *Erica* and *Cistus* species, *Ampelodesmos mauritanicus* (Poir.) T. Durand and Schinz and *Pinus halepensis* Mill., leading to mixed woods. Currently, the main forest formation of the island is the wild-olive maquis (*Prasio maioris-Oleatum sylvestris* O. Bolòs), a commonly dense community characterized by *Olea europaea* L. var. *syvestris* (Mill.) Lehr and presence of *Phillyrea* species and *Pistacia lentiscus* L. Other mixed formations also cover perturbed and open areas with pine woods, other maquis formations with *Erica* species, and garrigues (Bolòs et al., 1970; Bolòs, 1996; Fraga et al., 2015; Pons and Gómez-Pujol, 2003).

The vegetation of the Addaia area is representative of the northern Minorca landscape, characterized by a mosaic structure with crop fields and pastures alternating with dense silicicolous maquis (*Oleo sylvestris-Ceratonion siliquae* Br.-Bl. alliance) and pine woodlands. Close to the coast, cushy spiny shrubs expand including *Limonietum caprariensis* O. Bolòs and Molinier and *Launaetum cervicornis* O. Bolòs and Molinier, and the coastal maquis of *Aro picti-Phillyreetum rodriguezii* O. Bolòs, Molinier and P. Montserrat. Inland, a high maquis of the *Prasio-Oleatum* have a major coverage of wild olive and pine trees. The vegetation of the saltmarsh is mainly formed by communities of *Salicornion fruticosae* Br.-Bl. and *Arthronecmion glauci* Rivas-Martínez and Costa, with small woodlands of saltcedar (*Tamaricion africanae* Br.-Bl.) and patches dominated by sea-lavenders included in the *Limonion confusi* (Br.-Bl.) Rivas-Martínez and Costa.

1.2. Archaeological and historical background

Archaeological evidences of first human arrival to the Balearic

Islands occurred relatively latter compared to other Mediterranean insular territories such as Corsica or Sardinia where Neolithic human occupation is recorded, and earlier frequentations/occupations seem probable (Dawson, 2014), while the archaeological records of the Balearics lack of clear evidences from the Neolithic period (Micó, 2005, 2006). Nevertheless, the human colonization of the Balearic Islands is a slippery question in the archaeological literature. Although the timing of the first stable settlements is still debated, available dates from archaeological sites suggest their arrival to the island between 2900/2500 cal BCE (Guerrero et al., 2007; Guerrero and Calvo, 2008) and 2350/2150 cal BCE (Alcover, 2008; Lull et al., 2004; Sintes, 2015). An extended overview of the early colonization of the archipelago is out of the scope of this article, but we would like to remark that some sparse archaeological data could suggest sporadic frequentations of the island (e.g., Calvo et al., 2001; Gornés, 2016). In the case of Minorca, evidence of pre-Chalcolithic human presence can be deduced from isolated findings of lithic industry of presumably pre-Neolithic tradition (Fullola et al., 2005; Guerrero and Calvo, 2008; Guerrero et al., 2007) and from a stabling sequence of the rock-shelter of Cova dels Morts (Guerrero and Calvo, 2008; Mestres and de Nicolás, 1997; Guerrero et al., 2007; Bergadà and de Nicolás, 2005). Later on, Chalcolithic settlements are developed in all the islands, but the remains of this period are still rare, with the exception of Biniai Nou and Ses Roques Llisès archaeological sites (Sintes, 2015; Gornés, 2016).

At 1700/1600 cal BCE, a sedentary population and a demographic continuity throughout the archipelago was established, which corresponds to the Middle and Late Bronze Age (*naviform* period). From this moment onwards, megalithic monumental architecture appears in domestic structures (the so-called navetiforms). Around 1000–850 cal BCE Bronze Age societies experienced structural changes that culminate in the birth of the Early Iron Age Talayotic Culture characterized by megalithic buildings (Lull et al., 2008). From 550 cal BCE the destruction of some Talayotic villages is detected as well as the diversification of funeral rituals and the emergence of new religious monuments. These changes lead to the birth of Posttalayotic Culture (Late Iron Age), which extended until the Roman conquest of the Balearic Islands at 123 BCE (Guerrero et al., 2007). In the case of Minorca, the three main urban foundations are *Iamo*, *Mago* and *Sanisera*, the three located in the main anchorages of the island (Zucca, 1998; Riera Rullan, 2003). Roman domination lasted until 455 CE, when the Vandal conquest opened a period of instability with the domination and/or the relationship with Byzantium. This period ends with the conquest and domination of the archipelago by Muslims at 903 CE and later (1229 CE in Majorca and 1287 CE in Minorca) with the Christian conquest, which annexed the Balearic archipelago to the Catalano-Aragonese Crown. During the 18th century Minorca was annexed to Great Britain sovereignty, to be incorporated anew to the Spanish crown in the 19th century.

2. Material and methods

In September 2008, a 286-cm-long core was obtained with a 50 cm × 5 cm hand-operated Russian corer. The studied core was extracted from the central part of the Addaia lagoon (north of Minorca island, 39°59'23.4"N–4°12'21.6"E), where the highest sedimentary accumulation above the bedrock was achieved.

The methodology lies on a multi-proxy study combining off-site data including pollen, non-pollen palynomorphs (NPP), stomata, lithostratigraphy, charcoal particles, radiocarbon analyses and juniper macroremains. These data have been integrated with regional archaeobotanical and archaeological studies.

Four AMS radiocarbon dates were obtained at the BETA Analytic and Direct AMS laboratories (Table 1). Dated material corresponds to *Cerastoderma* sp., charcoal, pollen and seeds. Radiocarbon results were calibrated using the Intcal13.14C curve (Reimer et al., 2013). It has been established that ΔR value (local deviation from the global ocean reservoir age) for the Mediterranean surface waters around the Balearic

Table 1
Radiocarbon dates and calibrated ages.

Lab ID	Depth (cm)	Material	Date BP	Calibrated age 2 sigma
Beta - 287626	88–95	Charcoal	1970 ± 40	48 cal BCE–92 cal CE
Beta - 300340	110–115	<i>Cerastoderma</i> sp.	2620 ± 30	829–776 cal BCE
Beta - 300341	175–180	Seeds	3840 ± 40	2461–2199 cal BCE
D-AMS 013331	275–277	Pollen	5148 ± 31	4000–3934 cal BCE

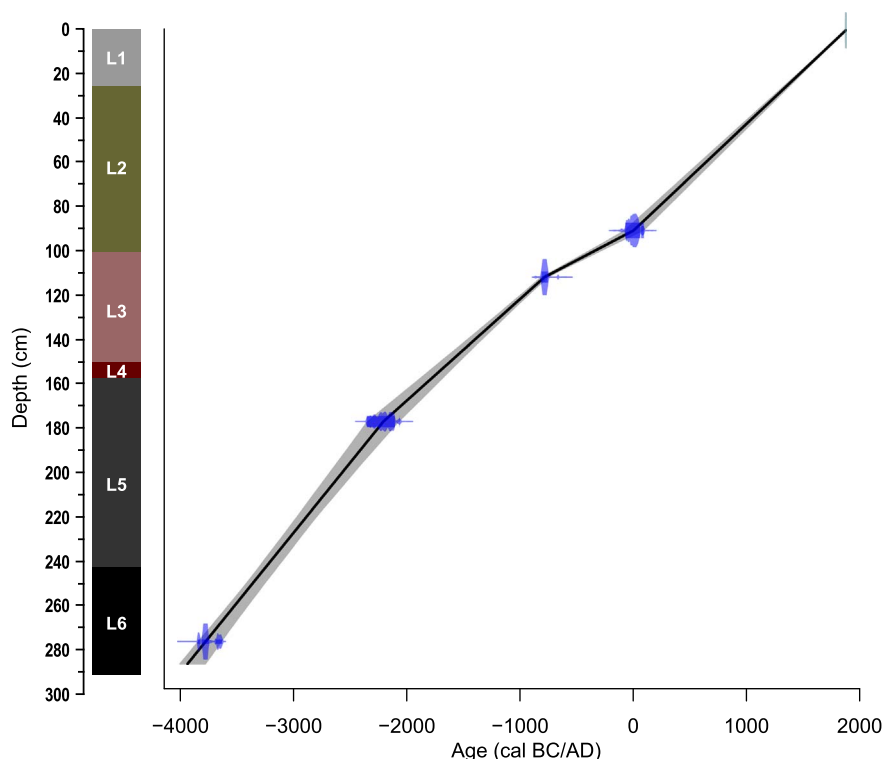


Fig. 2. Age-depth model of the Addaia sequence showing the probability distributions for selected calibrated dates. The interpolated model is represented as a solid black line and its 95% confidence interval as a grey band.

archipelago has been estimated in a value of 26 ± 24 ^{14}C radiocarbon years, due to the predominance of shallow water in the Balearic shore (Van Strydonck et al., 2010, 2012). For this reason, no marine reservoir correction has been applied for the *Cerastoderma* shell. The age–depth model was constructed by fitting an interpolated curve (Fig. 2) using the “CLAM” program (Blaauw, 2010) written in the statistical package “R” version 3.2.5 (R Development Core Team, 2016).

Thirty-four sedimentary samples were treated for pollen and NPP analyses using standard extraction techniques (Faegri et al., 1989). Mean average pollen sum is 350 dry land pollen grains. Pollen and NPP relative values were calculated as percentages of total land pollen sum of vascular plants omitting Cyperaceae, fern spores and aquatic taxa. Charcoal particles with a diameter $> 200\mu\text{m}$ were counted after sieving the sediment using pollen treatments. Charcoal particles and stomata values are expressed in number of particles by gram of dry sediment.

Pollen, stomata and NPP identification were carried out using published illustrations and morphological keys (e.g. Beug, 2004; Hansen, 1995; Moore et al., 1991; Punt et al., 1976–2009; Reille, 1992–1995; van Geel, 1978, 2001; van Geel and Aptroot, 2006). Cerealia pollen grains are defined as Poaceae grains exceeding $40\mu\text{m}$ in diameter, with an annulus diameter higher than $12\mu\text{m}$ (Faegri et al., 1989). *Cannabis*-t has been classified using the size criteria defined by Mercuri et al. (2002), while distinction between *Rumex acetosa* and *R. acetosella* types followed key-guides of Valdès et al. (1987). In this work we use the word Cichorieae instead of Cichorioideae, as proposed by

Florenzano et al. (2015) based on pollen morphology. The sum of apophytic taxa includes pollen types indicative of human impact (Behre, 1981) and synanthropic taxa described in local floras (Llorens et al., 2007; Fraga et al., 2015; Bolòs, 1996) while coprophilous fungi selection is based on specific works (e.g. van Geel, 2001; Ejarque et al., 2011). In this paper we use “SUM” (Σ) to refer the total count of taxa from the same taxonomic or ecological group (e.g. Ericaceae SUM corresponds to Ericaceae undiff., *Erica* and *Arbutus* pollen types). Test samples for plant macroremains have been studied between 286 and 160 cm, where *Juniperus* sp. stomata have also been quantified. Macroremains were recovered by sieving sediment samples through a mesh size of $250\mu\text{m}$ and identified using a binocular microscope at $\times 50$ magnifications with the help of standard keys of vegetation morphology (Castroviejo et al., 1986) and comparison with modern specimens of EMMA Herbarium (Universidad Politécnica de Madrid). Several adult leaf characters are included in the Iberian-Balearic *Juniperus* species classification key (Castroviejo et al., 1986) and some of them were found in the macrofossil fragments, such as the imbrication of scale-leaves and the scarious leaf margins (Fig. 3). The observation of herbarium material suggested that the presence of a depression at the underside of the scale-leaves was also a diagnostic feature for *Juniperus phoenicea* L.

Diagrams were constructed using the C2 program (Juggins, 2007), and stratigraphically constrained cluster analyses of percentage pollen values were carried out using the PAST 3.12 program (Hammer et al., 2001) to define Pollen and Non-Pollen Palynomorphs assemblage

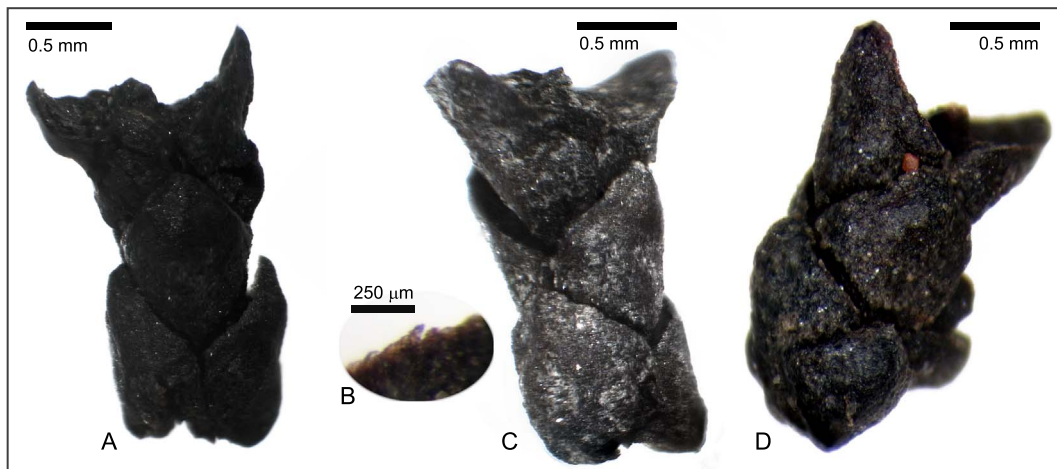


Fig. 3. Examples of macrofossils of *Juniperus phoenicea* from 267 to 268 cm depth (A) and 272–274 cm depth (B, C, D). The slight depression at the underside of scale-leaves can be better observed in lateral outline than in frontal position. Some remains of the scarious leaf margins are also observable in fig. B.

zones. Furthermore, rarefaction analysis was calculated to assess pollen richness to better understand the effects of human impacts and climate changes in large timescales (Birks and Line, 1992; Giesecke et al., 2012; Matthias et al., 2015). Ordination analyses were performed on pollen percentages using the vegan package (Dixon, 2003) of the R software (R Development Core Team, 2016). First, a Detrended Correspondence Analysis (DCA) has been done to select the adequate ordination method. Since the axis length was shorter than 3 SDs (2.10 SDs), linear ordination methods were preferable (Lepš and Šmilauer, 2003). Therefore, Principal Component Analysis (PCA) has been performed based on 62 pollen and NPP types after excluding rare taxa only present in a few samples, while the broken stick criterion was used to select significant axes.

Correlation coefficients between charcoal particle concentration and pollen percentages of selected taxa have been calculated for the period between ca. 3500 and 1000 cal BCE (ca. 5450–2950 cal yr BP) and tested for significance ($\alpha = 5\%$, two-sided) with Student's *t*-test (Table 2). This time span has been selected because it includes the transition from a presumably (near) natural closed environment to more human-induced open vegetation formations dominated by Mediterranean maquis (e.g. Noti et al., 2009; Tinner et al., 2005, 2006).

3. Results

3.1. Lithology and age-depth model

The 286 cm sedimentary sequence of Addaia is formed by six lithozones, presented in Table 3 and Fig. 2. Radiocarbon and calibrated dates are shown in Table 1. The age-depth model relies on four ^{14}C AMS measurements. The model incorporates the date 2008 CE for the modern surface of the sequence. Radiocarbon dates indicate that lagoon sedimentation started at the end of the 5th millennium cal BCE and

have supported a continuous sedimentation over the last 6100 years (Fig. 2).

3.2. Pollen, NPP, and charcoal particles zones

Cluster analysis allowed establishing three Pollen Assemblage Zones (PAZ), and five subzones. Pollen, NPP and rarefaction analysis results or summarized in Table 4 and shown in Fig. 4. In general, the first pollen zone (ADD-1) shows high AP pollen values (ca. 80%), with low presence of nitrophilous and ruderal taxa, relatively stable pollen richness values (ca. 28–32) and good preservation of pollen grains (< 10% of undifferentiated grains). The ADD-2 pollen zone records a decrease in the AP/NAP ratio from ca. 80% to 40%, concomitant to an increase in pollen richness, apophytic taxa, charcoal particles, but also undifferentiated pollen grains values rise until ca. 15% within this zone. Finally, the ADD-3 pollen zone supports in some way a forest recovery, mainly because of the *Pinus* and *Olea* expansion. This is concomitant to the expansion of Cichorieae and the decline in pollen richness.

3.3. Ordination analysis and charcoal/pollen correlation

The first PCA axis (Fig. 5) explains 61.2% of data variance, while the second one explains the 11.6% (total variance explained by the biplot is 72.8%). Positive values of the first axis are associated to *Juniperus*, deciduous *Quercus*, *Buxus*, undifferentiated ascospores and *Sporormiella*, whereas negative values are linked to *Olea*, *Pistacia*, Ericaceae SUM, *Cistus* SUM, Poaceae, *Asphodelus*, *Plantago lanceolata*-t, Cichorieae, *Plantago* SUM and Chenopodiaceae. Highest PCA axis 2 values are reached by Ericaceae SUM, *Asphodelus albus*-t, *Plantago lanceolata*-t, Asteroideae, *Plantago* SUM and undifferentiated ascospores, while lowest values are explained by *Pinus*, Chenopodiaceae and Cichorieae. The first axis may be interpreted as a gradient from a forested and barely perturbed environment (higher values) to a maquis-dominated landscape (lower values). The second axis can be understood as a *Pinus*-rich gradient, while negative values are also linked to several pollen human indicators such as *Plantago major/media*, *Trifolium arvense*-t, *Centaurea* or *Plantago* SUM.

Charcoal/pollen correlations are shown in Table 2. Maquis taxa, mainly *Olea*, *Pistacia*, Ericaceae SUM, *Cistus* SUM, Poaceae, *Plantago* SUM and *Rumex* SUM show significant positive correlation with charcoal concentrations, while deciduous *Quercus* present a negative correlation. Rarefaction analyses results are shown in Fig. 4.

Table 2
Correlation coefficients between pollen and charcoal particles. $\alpha = 5\%$, two-sided; level of significance: 0.44.

Taxon	Correlation coefficient
<i>Olea</i>	+0.50
Deciduous <i>Quercus</i>	−0.60
<i>Pistacia</i>	+0.45
<i>Cistus</i> Σ	+0.51
Ericaceae Σ	+0.51
Poaceae	+0.60
<i>Plantago</i> Σ	+0.55
<i>Rumex</i> Σ	+0.55

Table 3
Lithological descriptions for the Addaia core.

Sedimentary facies	Depth (cm)	Description
Lithozone 1	25–0	Reddish clays. Abundance of <i>Cerithium</i> , <i>Cerastoderma</i> , Foraminifera and <i>Hydrobites</i>
Lithozone 2	100–25	Bioclastic sands in a reddish clay matrix, with an increasing organic content. Abundance of <i>Cerithium</i> , <i>Cerastoderma</i> , Foraminifera and <i>Hydrobites</i>
Lithozone 3	150–100	Bioclastic sands in a greyish silt matrix, with an increasing content of organic matter. Abundance of <i>Cerithium</i> , <i>Cerastoderma</i> , Foraminifera and <i>Hydrobites</i>
Lithozone 4	157–150	Sandy silt level with abundance of malacofauna. Presence of ostracods, <i>Hydrobites</i> and Planorbidae
Lithozone 5	242–157	Fine sands and reddish bioclastic silts. Presence of ostracods, <i>Hydrobites</i> and Planorbidae
Lithozone 6	286–242	Fine bioclastic sands in clays. The faunal remains reveal the presence of ostracods, <i>Hydrobites</i> and Planorbidae

4. Discussion

4.1. Vegetation dynamics before clear human impact (ca. 4100–3500 cal BCE)

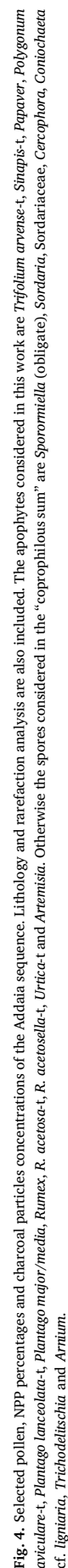
Mesophytic vegetation was rather important during the mid-Holocene in the Addaia area (Fig. 4). The Addaia palaeobotanical (ADD1a) data concerning this period reflects the dominance of apparently closed forests in a context of low or absent human activity. Furthermore, the positive values of samples from this zone in axis 1 and 2 in the PCA (Fig. 5) indicate the prevalence of a woody environment with dominance of natural coastal plant communities and a rather mesophytic tree cover. The relevant presence of a forested environment near the wetland is also indicated by the presence of saprophytic and/or parasitic fungi such as *Kretzschmaria deusta* and *Brachysporium* which could be related to the proximity of the host trees or to the presence of decomposed wood in vicinity of the drilling site (van Geel and Aptroot,

2006; Kiffer and Morelet, 1997; van Geel et al., 1980/1981). Hazel formations probably were restricted to inner part of the island and deep valleys, where more humid conditions and deeper soils prevailed. The moderate values of *Buxus* indicate the relevance of box formations in this island during the early and mid-Holocene (Pérez-Obiol et al., 2000), even that *Buxus balearica* Lam. is nowadays absent in Minorca but present in other Balearic Islands such as Mallorca and Cabrera (Lázaro, 2005).

As in Addaia's record, the mid-Holocene vegetation of Balearic Islands is formed by communities of *Ephedra*, *Pinus* and *Juniperus* as shown in diverse pollen sequences of Minorca (Yll et al., 1997, 1999; Burjachs et al., 2016a, 2016b). In this sense, the identification of *Juniperus phoenicea* macroremains and *Juniperus* sp. stomata concentration in the sequence of Addaia indicate its local presence supporting the noticeable role of this specie in littoral communities during this period, probably in rocky or sandy substrate as *Juniperus phoenicea* is found nowadays (Fraga et al., 2015; Bolòs et al., 1970; Bolòs, 1996; Rivas

Table 4
Main pollen, non-pollen palynomorphs and rarefaction analysis results from the Addaia sequence.

PAZ	Depth (cm)	Description
<i>ADD-3 (80–0 cm; ca. 1680 cal BP–present day/ca. 270 cal CE–present day)</i>		
ADD-3	80–0	Increase of the percentage of tree taxa (ca. 30–50%), mainly due to the expansion of <i>Pinus</i> and <i>Olea</i> . <i>Quercus ilex</i> -t, deciduous <i>Quercus</i> and <i>Juniperus</i> record only minor values. Among the shrubby taxa, <i>Pistacia</i> and <i>Cistaceae</i> values decrease while <i>Erica arborea</i> -t records the highest values in the sequence (15%). Herb taxa are mainly dominated by <i>Poaceae</i> (ca. 7–9%), <i>Asteroidae</i> (max. 5%) and <i>Cichorieae</i> (max. 22%). Other ruderal and nitrophilous taxa such as <i>Plantago lanceolata</i> -t and <i>Artemisia</i> are also recorded. Charcoal particles concentration reach maximal values at the beginning of the zone (9 particles/g). Several coprophilous fungi types are present with lower values (<i>Sporormiella</i> , <i>Sordaria</i> , <i>Coniochaeta</i> cf. <i>lignaria</i> and <i>Arnium</i>). Values of $E(T_n)$ fluctuate from 36 to 25.
<i>ADD-2 (168–80 cm; ca. 4050–1680 cal BP/ca. 2100 cal BCE–270 cal CE)</i>		
ADD-2b	120–80	Short living peak of <i>Ceratonina</i> and <i>Asphodelus albus</i> -t, the noticeable increase of <i>Pistacia</i> and <i>Cistus monspeliensis</i> . <i>Poaceae</i> and <i>Asteroidae</i> slightly decline at the end of the subzone. Coprophilous fungi and undifferentiated ascospores decline. $E(T_n)$ values are low at the beginning of the subzone (ca. 26) and increase progressively until 28 at the end.
ADD-2a	168–120	Sharp decline in arboreal pollen values (ca. 70 to 35%) mainly because of the drop of <i>Buxus</i> , <i>Juniperus</i> , <i>Pinus</i> , and deciduous <i>Quercus</i> . Spread of Mediterranean taxa such as <i>Olea</i> , <i>Quercus ilex</i> -t, <i>Pistacia</i> , <i>Cistus monspeliensis</i> , <i>Cistus salvifolius</i> and <i>Eicaceae</i> , mainly <i>Erica arborea</i> -t. <i>Juniperus</i> stomata drastically decline in this zone disappearing from 134 cm, while charcoal particles are constantly present (max. 5 particles/g). NAP is characterized by the predominance of <i>Poaceae</i> (max. 9%) and <i>Asteroidae</i> (max. 8%), the clear increase of <i>Plantago lanceolata</i> -t (ca. 6,5%) and <i>Plantago major/media</i> , accompanied by other apophytes such as <i>Asphodelus albus</i> -t, <i>Urtica</i> -t and <i>Rumex acetosa</i> -t. Presence of <i>Ceratonina</i> and first occurrence of <i>Juglans</i> . Other open ground taxa also expand or are present such as <i>Anthemis</i> -t, <i>Aster</i> -t and <i>Carduus</i> -t. Cerealia-t pollen show scattered occurrences (values < 1%). NPP assemblage is dominated by undifferentiated ascospores, <i>Sporormiella</i> and <i>Glomus</i> . A diversified coprophilous fungi spectrum is recorded, including <i>Podospora</i> , <i>Arnium</i> and <i>Delischia</i> . Values of $E(T_n)$ show a remarkable increase from ca. 30 to 36, decreasing to 26 at the end of the zone.
<i>ADD-1 (283–168 cm; ca. 6050–4050 cal BP/ca. 4100–2100 cal BCE)</i>		
ADD-1c	198–168	Highest values of AP (max. 86%). increase of the values of heliophilous trees such as <i>Pinus</i> and <i>Juniperus</i> . Slight decrease of deciduous <i>Quercus</i> , <i>Quercus ilex</i> -t, <i>Castanea</i> and <i>Corylus</i> and <i>Buxus</i> . Expansion of <i>Poaceae</i> and presence of nitrophilous and ruderal taxa such as <i>Asphodelus albus</i> -t, <i>Plantago major/media</i> and <i>Urtica</i> -t. <i>Juniperus</i> stomata reach values of 11 particles/g while charcoal particles record regular values (4,5 particles/g). Increase of <i>Sporormiella</i> and presence of a diversified coprophilous fungi assemblage (i.e. <i>Podospora</i> , <i>Sordaria</i> and <i>Sordariaceae</i>). The values of $E(T_n)$ present a decreasing trend throughout the zone, from 31 to 24.
ADD-1b	248–198	<i>Pinus</i> and <i>Buxus</i> decrease at the beginning of the zone, while <i>Juniperus</i> , deciduous <i>Quercus</i> , <i>Corylus</i> and <i>Castanea</i> increase. <i>Ceratonina</i> appears for the first time. <i>Buxus</i> is still the main shrubby taxa, accompanied by <i>Ephedra fragilis</i> and <i>Pistacia</i> , while <i>Erica arborea</i> -t increase at the end of the subzone. Increase of <i>Poaceae</i> (ca. 5%), and first occurrences of <i>Cerealia</i> -t. The apophytes slightly increase, with the first recordings of <i>Urtica</i> -t and <i>Rumex acetosa</i> -t. Diversification of heliophilous and meadow taxa such as <i>Scrophulariaceae</i> , <i>Fabaceae</i> , <i>Astragalus</i> -t and <i>Lotus</i> . <i>Juniperus</i> stomata concentration is high but uneven (1 to 14 particles/g). Increase of <i>Sporormiella</i> more diversified assemblage of non-obligate coprophilous fungi. Higher values of <i>Glomus</i> . Values of $E(T_n)$ are moderate and fluctuate between 25 and 34.
ADD-1a	283–248	High values of AP (ca.65–85%), dominated by <i>Juniperus</i> , deciduous <i>Quercus</i> and <i>Quercus ilex</i> -t. Moderate values of <i>Corylus</i> , <i>Castanea</i> and <i>Betula</i> . Shrubby taxa dominated by <i>Buxus</i> and <i>Ephedra fragilis</i> . NAP is dominated by <i>Asteroidae</i> and <i>Poaceae</i> . High values of <i>Juniperus</i> stomata. Occurrence of apophytes such as <i>Papaver</i> , <i>Asphodelus albus</i> -t and <i>Plantago lanceolata</i> -t. Charcoal concentration reach values up to 5 particles/g. High values of <i>Sporormiella</i> (ca. 14%), and presence of other coprophilous fungi such as <i>Sordaria</i> or <i>Cercophora</i> . Occurrence of saprobe or parasitic fungi such as <i>Kretzschmaria deusta</i> and <i>Brachysporium</i> . Oscillating pattern of pollen richness: $E(T_n)$ fluctuating from ca. 28 to 34.



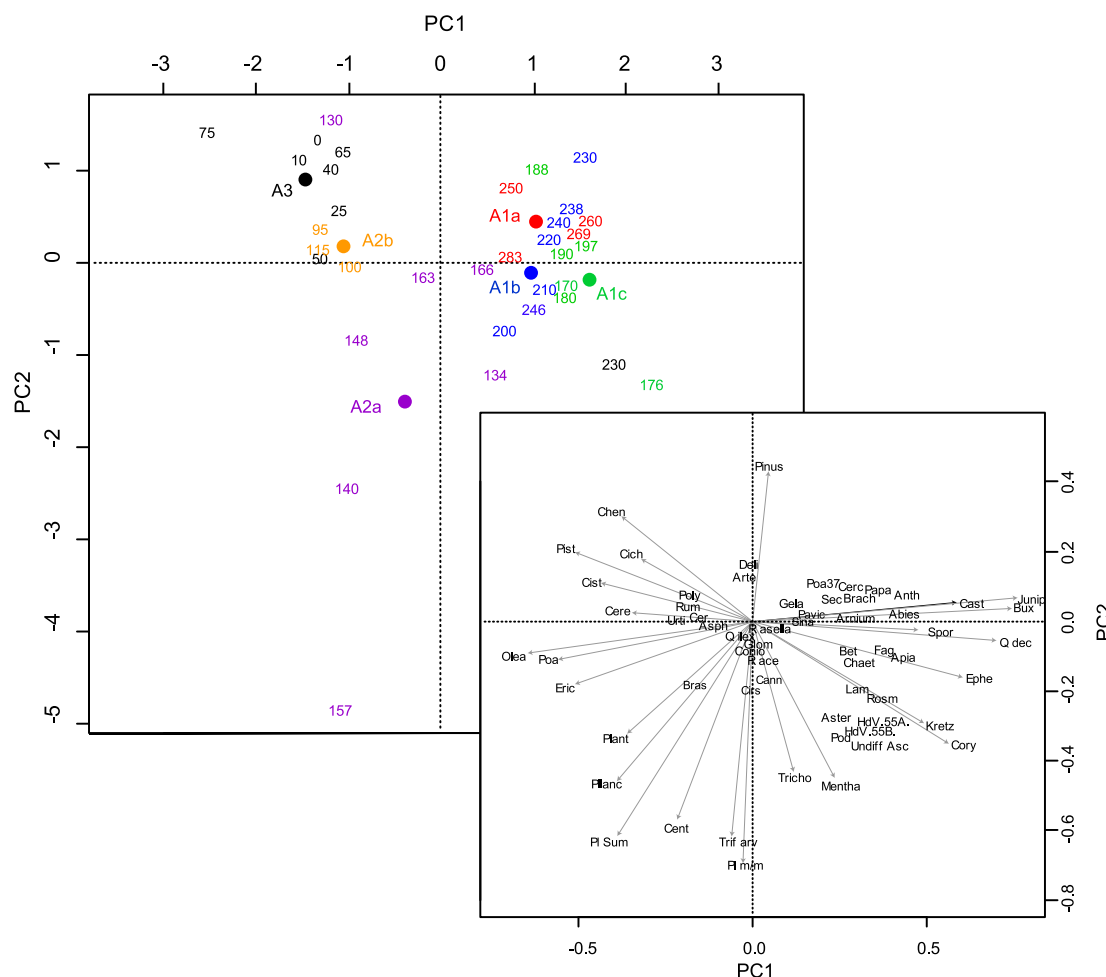


Fig. 5. Principal components analysis (PCA) of the Addaia sequence data. The centroids are derived from the cluster analysis used in the pollen zones.

Martínez et al., 1992). Otherwise, the continuous curve of *Castanea* pollen (ca. 3%) probably reflects the long-transport pollen from the closer quaternary chestnut refuges located in continental areas such as south-eastern Spain and south-eastern France (Krebs et al., 2003; Carrión et al., 2003). This vegetation composition has also been observed in other pollen sequences of Minorca, specifically Cala en Porter, Algendar, Cala Galdana, Son Bou, Hort Timoner and Es Grau (Yll et al., 1994; Yll et al., 1997, 1999; Burjachs, 2006; Burjachs et al., 2016a, 2016b). The sequence of S'Albufera d'Alcúdia in Mallorca Island also shows a similar vegetation composition during the first half of the Holocene, recording plant communities formed by *Juniperus*, *Ephedra*, *Quercus*, *Buxus* and *Corylus* (Burjachs et al., 1994, 2016a, 2016b).

Anthropogenic pollen indicators (API) are weak during this phase, with occurrences of *Papaver*, *Asphodelus albus*-t, *Plantago lanceolata*-t, *Rumex* and *Artemisia*. As pointed out by [Burjachs et al., 2016a](#), occurrences of API appear in the Balearic pollen records even during the early-Holocene. In this sense, such weak values cannot be viewed as human activities because the lack of changes in other proxies such as charcoal particles, NPP or a decrease in the AP pollen values. In this period, noticeable values of dung-related fungal spores including the obligate coprophilous fungi *Sporormiella*, as well as *Cercophora* and *Coniochaeta* cf. *lignaria* which are commonly found and even specialize on herbivore dung ([Davis and Shafer, 2006](#); [Ejarque et al., 2011](#)), have been found during this phase. Nevertheless, during the early and mid-Holocene endemic fauna such as the goat-like deer *Myotragus balearicus* is present in Mallorca and Minorca, being the more modern *Myotragus* dated at 3963–3766 (95.4%) cal BCE in Pas d'en Revull ([Bover and Alcover, 2003](#); [Bover et al., 2016](#); [Quintana et al., 2003](#)). The

microfossil study carried out on fossil coprolites of *Myotragus baleareicus* shown the presence of *Sordaria*, *Sporormiella* and *Gelasinospora* in coprolites (Welker et al., 2014). Caprinae were introduced with the definitive colonization of Minorca, being the most ancient evidence in Talatí de Dalt dated at 2033–1889 cal BCE (KIA-19500: 3605 ± 30 yr BP; van Strydonck et al., 2005), while the later *Myotragus* in Minorca has been dated at 3963–3766 (95.4%) cal BCE in Pas den Revull (Beta-177237: 5060 ± 40 yr BP; Quintana et al., 2003). Considering the presence of *Myotragus* in Minorca during this period and the absence of humans and domestic animals, the high values of coprophilous fungal spores in the Addaia sequence must not be related to the presence of domestic herbivores but likely to the frequentation of the wetland and wet grasslands by wild fauna. Faunal composition from the Addaia sequence indicates the predominance of fresh water conditions that contributed to the expansion of these attractive wet grasslands.

The noticeable values of mesic taxa such as *Corylus*, deciduous *Quercus* and *Buxus* in Gymnesic sequences indicate the prevalence of more wet climatic conditions and less rainfall seasonality than in current Mediterranean regime (Pérez-Obiol et al., 2000; Yll et al., 1997; Pérez-Obiol and Sadori, 2007). Paleoclimate data from Siles and Laguna de Medina in southern Spain (Reed et al., 2001; Carrión, 2002) and high lake-levels in Lake Preola in Sicily (Magny et al., 2011, 2013) corroborate the occurrence of a more humid period during the mid-Holocene in the southern part of western and central Mediterranean. All these evidences suggest wetter-than-present climate conditions (winters and summers) from 6050 to 3550 cal BCE (8000–5500 cal yr BP). This climate regime likely resulted from the orbitally-driven northern

position of the intertropical convergent zone (Haug et al., 2001) which favoured a shift in the westerlies transporting more moisture to the southern Mediterranean during the mid-Holocene (Vanni  re et al., 2011; Tzedakis, 2007; Magny et al., 2013). In the Minorcan sequences, the mesophytic optimum seems to finish at ca. 6th to 5th millennia cal BCE (ca. 7–6 cal kyr BP), with similar pattern and timing with the start of a progressive drying trend attested by increasing Saharan dust in southern Spain (Jim  nez-Espejo et al., 2014). This change in climate conditions coincides with relative declines of mesic trees and shrubs in the Majorcan and Minorcan sequences (Burjachs, 2006; Burjachs et al., 2016a, 2016b; Yll et al., 1997).

4.2. First agropastoral activities in a closed wooded environment (3500–2100 cal BCE)

This environmental phase records a similar vegetal landscape than the former one, with a coastal vegetation dominated by *Juniperus*, and forests formed by *Buxus*, deciduous *Quercus*, *Quercus ilex*-t and *Corylus*. This vegetation composition is confirmed by ordination analysis with ADD-1b (ca. 3500–2650 cal BCE) and ADD-1c cluster group on the positive values of PCA axis 1 (Figs. 4 and 5). Between ca. 3500 and 3100 cal BCE, a diversification of human pollen indicators is recorded, with the first appearance of crop taxa and some weeds and nitrophilous taxa such as *Urtica*-t and *Rumex acetosa*-t. This fact is coeval to the slight decline of box and pines and the increase of some meadow and heliophilous taxa such as *Scrophulariaceae*, *Fabaceae*, *Astragalus*-t, *Lotus*-t and *Rubiaceae*, suggesting the onset of agropastoral activities in a context of mobile practices which do not imply permanent forest clearances as shown by the punctual retreat of AP values. In this sense, the diversification of coprophilous fungi such as *Podospora*, *Sordaria* or *Trichodelischia* suggests a more intense presence of herbivores in the wet areas. Such forest clearances in the Addaia surroundings may have produced an increase in soil erosion as suggested by the increase of the endomycorrhizal fungi *Glomus* cf. *fasciculatum* (van Geel et al., 2003).

The sequence of Es Grau, which is just 8 km far from Addaia, similarly records a marked increase of *Olea*, *Plantago*, *Poaceae*, *Erica* and *Cerealia*-t pollen from ca. 3300 cal BCE, which is interpreted as the beginning of the vegetation transition towards maquis formations in north-eastern Minorca (Burjachs, 2006; Burjachs et al., 2016a, 2016b) and indicates the creation of forest clearances, a fact that is also slightly recorded in Addaia. Both sequences suggest the presence of Neolithic agropastoral activities at the end of the fourth millennium cal BCE.

The first occurrences of *Ceratonia* pollen in Addaia could suggest the presence of this tree in Minorca during this period. Nevertheless, the significance of this data is difficult to assess since archaeobotanical and palaeobotanical data in the Mediterranean is still too scarce to precisely define the timing and expansion routes for his taxon in the past (Zohary et al., 2012; Ram  n-Laca and Mabblerley, 2004). Nevertheless, the fact that in the Addaia sequence the first occurrences of carob trees coincide with the probable introduction of agropastoral practices in Minorca, suggests that they could also have been favoured by Neolithic agricultural activities. The human presence in the Addaia area is archaeologically attested, as shown by Cova des Morts rock shelter, a *fumier* sequence (sedimentary sequences formed by livestock activity in caves or rock-shelters) dated at the Bronze Age period (Mestres and de Nicol  s, 1997; Bergad   and de Nicol  s, 2005). Nonetheless, one of these burnt layers has been dated at ca. 3525–3080 cal BCE (UBAR-418), prior to Early Bronze Age and coincides with evidences of human practices in the Addaia sequence. Based on this date, some authors proposed that this site has an earlier use of this *fumier* sequence (Guerrero et al., 2007; Guerrero and Calvo, 2008). Despite the fragmentary nature of this archaeological data, paleobotanical data of Addaia and Es Grau sequences suggests the existence of human presence in this north-eastern part of Minorca at this period.

From ca. 2650–2100 cal BCE (subzone ADD-1c), the progressive decline in box and oak woods is coeval with the increase of nitrophilous

and ruderal taxa, mainly *Asphodelus albus*-t and *Plantago major/media*-t with occurrences of *Urtica*-t, *Rumex*, *Rumex acetosa*-t, *Polygonum aviculare*-t and *Artemisia*. Besides, the increase of coprophilous fungi (including *Sporormiella*, *Sordaria*, *Sodariaceae*, *Cercophora* and *Coniochaeta* cf. *ligniaria*) confirm the presence of herbivores near the lagoon. In addition, the increase in grasses and the recurrence of charcoal particles within this subzone suggest the creation of forest clearances for pastoral purposes during the Chalcolithic period. This phase of increasing human activities correspond to the accepted definitive occupation of the Balearic Islands (Guerrero et al., 2007; Sintes, 2015).

Taken together, all these evidences put forward the first human disruption of this island environment around the end of the fourth millennium cal BCE, even if we need more data to assess the dimension of the impact of the humans on such insular landscape.

4.3. The expansion of agropastoral activities and the deep environmental transformation (2100 cal BCE–270 cal CE)

At ca. 2100 cal BCE (subzone ADD-2a) a deep and sudden landscape change occurred implying the substitution of mesophytic vegetation by Mediterranean maquis formation dominated by wild olives, heathers, mastic and *Cistaceae* at ca. 2100 cal BCE (Fig. 4, Table 4). Such deep environmental change in Addaia (Add-2a) is also observed in the PCA as shown by the transition from positive to negative values in the first axis between 166 and 163 cm depth (ca. 2100 to 1900 cal BCE) indicating the expansion of maquis and garrigues while negative values in the second axis suggest the development of open littoral pastures (Fig. 5). The simultaneous decline of both *Pinus* and *Juniperus* (in pollen and stomata concentration) suggest change of dune and post-dune vegetation. Contrastingly, the vegetation transition from mesophytic-dominated landscape to a maquis environment in the Addaia sequence has been recorded with different timings in all the Gymnesic pollen sequences: ca. 3300–3000 cal BCE in Es Grau (Burjachs, 2006; Burjachs et al., 2016b), 2780–2550 cal BCE in Algendar (Yll et al., 1997), 4180–3900 cal BCE in Cala'n Porter in Minorca and ca. 3200–2800 cal BCE in S'Albufera d'Alc  dia in Majorca (Burjachs et al., 2016a, 2016b). Such chronological incongruence is partly possibly linked to the difficulty in constructing unequivocal age-depth models with a reduced number of radiocarbon dates.

The diversification of open-ground herbaceous taxa such as *Anthemis*-t, *Aster*-t, *Carduus*-t, *Cirsium*-t or *Lotus*-t in the Addaia sequence coincides with the appearance of land glades. In this respect, agro-pastoral activities were present as indicated by the expansion and diversification of apophytes (mainly *Plantago lanceolata*-t, *Plantago major/media*, *Trifolium arvense*-t and *Sinapis*-t) while the expansion of herbs (mostly *Poaceae* and *Asteroidae*) support landscape openness. The presence of *Ceratonia* and the first occurrence of *Juglans* pollen suggest the presence of carob and walnut trees in this northern part of Minorca during the Chalcolithic to Bronze Age transition. Pollen grains of *Juglans* have also been reported in Sardinia and Sicily with timings between 2800 and 2500 cal BCE (Di Rita and Melis, 2013; Sadori et al., 2013). Furthermore, regional fire activity seems to increase simultaneously as deciduous and mesic taxa decline and pollen human indicators increase. Pollen/charcoal correlations for the period between ca. 3450–950 cal BCE show that fire activity harms oaks, favouring the expansion of maquis and anthropogenic taxa such as *Olea*, *Pistacia*, *Cistus*, *Ericaceae*, *Poaceae*, *Plantago* and *Rumex*. The increase of *Pistacia lentiscus* and *Cistus* as post-fire early successional species in Mediterranean environments has also been defined in modern ecological and botanical works (Roy and Sonie, 1992; Mont  s et al., 2004; Ladd et al., 2005; Morey and Gil, 1983; De Luis et al., 2006). The prevalence of *Pistacia* and *Erica* is also well represented in the anthracological record of Minorca (Table 5). Additionally, the pollen richness increases suddenly at ca. 2100–1900 cal BCE, suggesting that human disturbances increased diversity of species and vegetal communities in Addaia area. All these data suggest that forest clearances and agro-sylvo-pastoral

Table 5

Synthesis of the anthracological results of Minorca.

Taxa	Chrono-cultural phase	c. 1700-1450 cal BCE, Early Bronze Age	1450-900/800, Middle-Late Brone Age		900/800-550, Early Iron Age	550-123 cal BCE, Late Iron Age				s. II cal BCE- S. 1 cal CE, Romanization	s. XIV-XVIII cal CE, Late Medieval- Early Modern
	Site name	Cova des Mussol	Cova des Càrritx	Biniparratx petit			Torre Gaumés	Cúrnia Nou	Talatí	Biniparratx petit	
	Type of site	Funerary cave	Funerary cave	Settlement			Settlement	Settlement	Settlement	Settlement	
	Chronology cal BCE	1550 cal BCE	1450/1400-800 cal BCE	1000-800 cal BCE	770-480 cal BCE	s. V-II cal BCE	S. IV cal BCE	S. II cal BCE	s. IV-I cal BCE	SII cal BC-SI cal CE ¹	S XIV-XVIII cal CE ²
Trees	<i>Pinus halepensis</i>	*		*							
	<i>Quercus evergreen</i>						*				
	<i>Ficus carica</i>		*								
	<i>Olea europaea</i>										
Sclerophyllous shrubs and lianas	<i>Arbutus unedo</i>						*				
	<i>Erica</i> sp.							*		*	
	<i>Pistacia lentiscus</i>	*		*	*						
	<i>Cistus</i> sp.	*	*					*			
	<i>Rhamnus-Phillyrea</i>						*	*	*	*	
	<i>Rosmarinus officinalis</i>										
	<i>Clematis</i> sp.		*								
Other taxa	<i>Pistacia tp. terebinthus</i>									*	
	<i>Prunus</i> sp.				*						
	<i>Juniperus</i> sp.		*								
	Fabaceae								*		
	Monocotyledon										
Legend		Dominant (>25%)	¹ Sample with 43 analyzed fragments; ² sample with 80 fragments analyzed. Res of the samples >120 fragments								
		Frequent (10%-25%)	References: C. Mussol (Piqué, 1999a), C. Càrritx (Piqué, 1999b), Biniparratx (Euba, 2005; Noguera, 2002; Celma and Hernández-Gasch, 2011), Torre Gaumés (Euba, 2005), Cúrnia N. (Picornell, 2010), Talatí (Piqué, 2005)								
		Occasional (10%-3%)									
	*	Present (<3%)									

activities played a key role in the construction of a patchy cultural landscape formed by maquis, garrigues, agricultural and pastoral areas. In this regard, palynological studies in Sicily have also revealed the development of maquis/garrigues and open areas during the Holocene in relation to land-use practices (Tinner et al., 2016; Noti et al., 2009).

Besides, noticeable values and diversification of coprophilous fungi such as *Sporormiella*, *Podospora*, *Sordaria*, other Sordariaceae, *Cercophora*, *Delitschia*, *Trichodelitschia*, *Coniochaeta* cf. *lignaria* and *Arniun* highlight the development of pastoral activities nearby the lagoon during this period, as the endemic fauna have most likely disappeared at this moment. As initiated in the subzone ADD-1c (ca. 2650–2100 cal BCE), the noticeable values of charcoal particles suggest the recurrence of fires either for agropastoral purposes or due to a drier climatic trend. Increase in fire frequencies follow the same pattern than others south of 40°N latitude sites, such as Lake Siles in south-eastern Spain (Carrión, 2002) or Mistras lagoon in southwestern Sardinia (Di Rita and Melis, 2013), where increased fire activity is observed since ca. 3000–2000 cal BCE. During the Chalcolithic a definitive human population is established in Minorca, while during Middle-Late Bronze Age a monumental megalithic domestic architecture emerges coinciding with the occupation of all island biotopes (Guerrero et al., 2007). Therefore, the use of fire by human populations for agropastoral purposes should be considered.

This general vegetation change in Minorca is shortly preceded or occurs simultaneously with heliophilous taxa, which could reveal clearances due either human and fire post-disturbance vegetation such as *Erica*, Poaceae or Cistaceae, coeval with the increase in certain crops and apophytes taxa (Cerealia-t or *Plantago* species). Although the increase of *Plantago* could be partly due to the development of coastal marshes, as the presence of the halophyte *Plantago crassifolia* Forssk. is attested (Llorens et al., 2007; Vicente et al., 2004). *Plantago crassifolia* pollen is included within the *Plantago coronopus*-t in pollen morphological works (Uberta et al., 1988), and this pollen type presents weak values all along the Addaia sequence. Plantaginaceae currently growing in the Balearics are abundant in human-disturbed environments and it can be considered a reliable human indicator. The expansion of human-induced taxa coinciding with the vegetation change has also been

recorded in other sequences of both the northern and southern part of Minorca (sequences of Es Grau, Cala en Porter and Algendar: Yll et al., 1999; Burjachs et al., 2016a, 2016b). According to this, *Plantago* species increase in the mid- to late-Holocene transition in Gymnesic diagrams should be considered at least partly as a human disturbance indicator because of its coincidence with other API in the pollen diagrams.

A parallel proxy to be considered in order to evaluate the role of humans in the shaping of landscape in Menorca during the first millennia of sedentary agro-pastoral population is the anthracological record (Table 5) from archaeological sites such as Cova des Mussol (Piqué, 1999a), Cova des Carritx (Piqué, 1999b), Biniparratx (Euba, 2005; Noguera, 2002; Celma and Hernández-Gasch, 2011), Torre de'n Gaumés (Euba, 2005), Cúrnua Nou (Picornell-Gelabert, 2010) and Talatí (Piqué, 2005). Charcoal illustrates the recurrent use of woody biomass as firewood. This is thus one of the core social actions concerning the material relations between humans and vegetation. The anthracological data available in archaeological sites of Menorca shows that, from the beginning of Bronze Age (c. 1700–1450 cal BCE) the woody plants collected corresponds to Mediterranean sclerophyll species (Table 5), mainly wild olive trees. Pines appear scarcely during the sequence and are absent in different sites. While *Quercus ilex/coccifera* is only present with very minor values in just one of the sites studied, taxa with a higher representation and high continuity such as *Olea europaea*, *Arbutus unedo*, *Erica* sp., *Rhamnus/Phillyrea* sp. and *Cistus* sp., provide evidence for important development of open and semi-open maquis formations in the island. This data suggests that since the first centuries of sedentary human occupation of the island, the landscape change identified earlier by pollen sequences is already consolidated. The anthracological record up to the Roman period shows a clear predominance of sclerophyll Mediterranean maquis species used as firewood (Table 5) and an establishment of Mediterranean thermo/mesomediterranean vegetation during the second millennia cal BCE, when the early human presence is archaeologically detected in the island.

The somewhat sudden change in fire activity in the Western and Central Mediterranean about ca. 3550–3050 cal BCE (ca. 5500–5000 cal yr BP) has been related to a threshold reaction to the

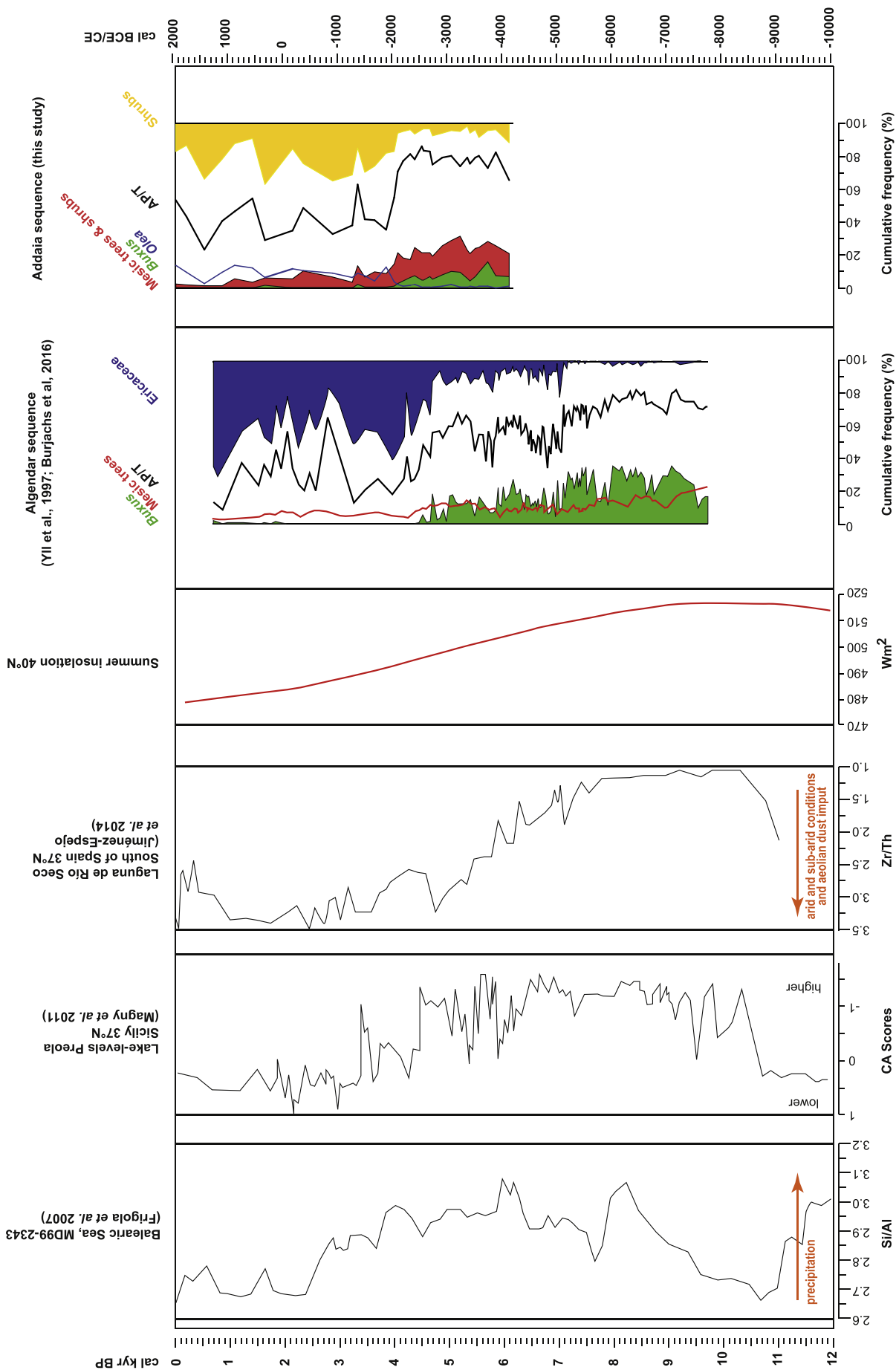


Fig. 6. Selected climate data from the western Mediterranean and pollen curves of Algendar and Addaia sequences.

gradual southward migration of the ITCZ and the collapse of the Afro-Asian-monsoon system (Vannière et al., 2011). Sediment composition data from the Balearic Sea suggests a reduction in river run-off (decrease in Si/Al ratios) from the mid-Holocene towards the present, suggesting drier conditions in Northern Minorca (Frígola et al., 2007; Fig. 6). In this sense, ecological works have pointed out the high solar irradiance and summer drought as the main factors of seedling mortality in *Buxus balearica* (Lázaro et al., 2006), suggesting that augmented seasonality and long summer dry could affect the renewing of box formations.

The environmental change recorded in Gymnesic sequences has been related to major climatic transformations in the Western Mediterranean during the mid- to late-Holocene transition (Burjachs et al., 1994, 2016a; Pérez-Obiol et al., 2000; Pérez-Obiol and Sadori, 2007; Yll et al., 1997), and has been defined as sharp by some authors in a context of climate change towards more arid conditions (Welker et al., 2014). However, the available radiocarbon data of this vegetation change do not support the hypothesis of sudden landscape change due to climatic changes, but a gradual transition with micro-regional to regional variability. The application of the “aridification hypothesis” to explain Balearic vegetation changes omits the additional resilience capacity of mesic communities living in the islands during the mid-Holocene. For instance, it has been shown that *Buxus balearica* formations tend to survive for long periods under unfavourable ecological conditions for recruitment because of the huge longevity of the individuals, which hence delays the possibility of its extinction (Lázaro et al., 2006).

The available radiocarbon data and the agropastoral indicators in Minorcan pollen sequences proposes a more gradual transition to the deep landscape change, probably with microregional variability where human activity could have played a key role (Figs. 4 and 6). Otherwise, the spread of drought-adapted plant communities (implying increased flammability) and the general rise of human disturbances in a context of drier environmental conditions seem to explain the increased fire activity, as has been observed in other sites south of 40°N (e.g., Vannière et al., 2011; Tinner et al., 2016; Noti et al., 2009). In this sense, human communities use the fire for land clearance to practice husbandry, promoting forest clearances which were progressively occupied by plant communities more adapted to changing climate towards dry conditions. In this sense, mesophytic forest environments were not fire-prone in comparison to more flammable garrigues, maquis and grasslands, which are also more adapted to summer drought, likely contributed to their extinction or drastic reduction within the island. It seems probable that micro regional divergences in the vegetation transition may be related to different anthropization rhythms, microclimatic/topographic factors and the proximity to termo-Mediterranean vegetation refuges in the island in a context of increasing dryness and seasonality in the mid- to late-Holocene transition.

During Late Bronze Age and Early Iron Age (subzone ADD-2b) a retreat in pine woods is observed coeval to an increase of scrublands as attested by the increase of mastic and heather values related with the continuity of fires recurrence. Wild fires were probably used for the expansion of pastoral activities in the area, as evidenced by moderate values of apophytes such as *Plantago lanceolata*-t, *Asphodelus*, *Rumex* or *Urtica*-t and coprophilous fungi. A slight decline in pastoral activity nearby the lagoon can be suggested by less diversity of API and coprophilous fungi during the second half of the first millennium cal BCE (upper ADD-2b zone, Late Iron Age or Post-Talayotic period) and Roman times, coinciding with a decline in fire frequency. Otherwise, occurrences of cereal pollen suggest the existence of regional agricultural activities, while the slight increase of *Ceratonia* pollen during Late Bronze Age and Early Iron Age (Naviform and Talayotic periods) suggest the presence of carob tree arboriculture in the island, considering the severe underrepresentation of *Ceratonia* pollen in the fossil records (Jahns, 2003; Bottema and Sarpaki, 2003).

The Late Bronze Age (1400–850 cal BCE) implies the increase of external trade, as shown by the spread of coastal sites probably used as

a hinge between maritime routes and terrestrial exchanges in the shore (promontories and anchorage sites) both between the islands of the archipelago or from outside. During this period the cultural confluence between Mallorca and Minorca is evident (Calvo Trias et al., 2013; Guerrero et al., 2007; Lull et al., 1999; Calvo and Galmés, i.p.). Such cultural process may have produced new types of landscape management, as for instance the spread of carob tree sylvoculture as shown by Addaia sequence. Both Bronze Age and Iron Age, correspond to demographic increases, effective occupation of islands biotopes, and territorial control through monumentality of different types of dry-stone buildings (Gornés, 2016; Calvo, 2009). The human use of the Addaia territory is also confirmed by Bronze Age and Iron Age archaeological sites and surface materials recovered through extensive survey (Fig. 1; Servera-Vives et al., 2017).

An overview of this environmental phase highlights the complexity of human-climate-environmental relationships mainly from the late-Holocene. In this sense, it seems that maquis, garrigues and clearings were favoured by human action in a context of increasing dryness and seasonality that promoted vegetation flammability and the substitution of former mesic communities to more adapted termophilous vegetation. The numerous pollen studies in Minorca (Burjachs et al., 2016a, 2016b; Yll et al., 1997) highlight different micro-regional vegetation histories in relation to uneven anthropisation rhythms, different resilience responses of the vegetation composition, microclimate and topographic conditions and the proximity of clusters of water-stress-adapted vegetation.

4.4. Historical dynamics in the Addaia environment (ca. 270 cal CE–present day)

The second half of the first millennium cal CE (Vandal period) records a certain recovery of the tree cover, mainly of *Pinus* and *Olea*, and the decrease of some Mediterranean shrubs such as *Cistus monspeliensis*, *Pistacia* and *Ericaceae* (Fig. 4). This forest recovery is also associated with the decline of fire activity and several apophytes. However, other herbs such as *Poaceae*, *Asteroidae* and *Cichorieae* appear with moderate values, suggesting a rather maintenance of open areas. The short-living peak of *Sporormiella* implies local grazing nearby the lagoon at that time.

From ca. 900–1100 cal CE onwards (from Muslim and Christian conquests), pine and (wild) olives woods record noticeable reductions, while holm-oak woodlands and scrublands (mainly heathers and mastic) progressively increase. The spread of *Quercus ilex* forests is recorded together with (wild) olive expansion in Es Grau sequence (north-eastern Minorca) at ca. 900–1100 cal CE (Burjachs, 2006; Burjachs et al., 2016a), suggesting that holm-oaks and olive-trees may have been favoured by humans during this period. The recovery of some apophytes (mainly *Plantago* pollen types), the noticeable increase of *Cichorieae*, the presence of *Sporormiella* and the charcoal particles concentration suggest the existence of pastoral activities at local scale. The curve of *Cichorieae* has a complex interpretation in terms of relationships with human presence: it can reflect both the presence of some dry-resistant communities on natural open areas or it can be related to secondary open-habitats by the spread of pastures (Florenzano et al., 2015; Florenzano et al., 2013; Mercuri et al., 2010; Cremaschi et al., 2015). In off-site pollen records, *Cichorieae* pollen, when accompanied with *Poaceae* increases, usually reflects the extension of dry-grassland during increasing climate aridity and human impact during the late-Holocene (Mercuri et al., 2012). In this sense, our data indicates a turn-over to agropastoral practices which promoted dry pastures from the Christian conquest.

5. Conclusions

The multi-proxy study of the sequence of Addaia reveals the complex history of human-climate-vegetation interactions during the mid-

and late-Holocene in a Mediterranean island environment, reflecting how newcomers induce new landscapes under changing climate conditions. Addaia sequence agrees with other paleoenvironmental studies carried out in the Gymnesics, indicating that a forested environment prevails during the mid-Holocene with widespread mesic communities favoured by moister-than-today conditions and low (or absent) human impact. The first human arrival in the Balearic Islands seems difficult to detect both by archaeological and paleoenvironmental data. Nevertheless, Addaia's multi-proxy study furnishes new data supporting the possibility of a pre-Chalcolithic discovery and frequentation of the Balearic Islands during the Neolithic period, implying mobile agro-pastoral practices, as evidenced by the expansion of a rather open-vegetation dominated by maquis and garrigues coinciding with the spread of anthropogenic pollen indicators in Minorca at ca. 3300–2100 cal BCE. Even though the climate change background (increasing dryness and seasonality) seems to have played a noticeable role changing the physiognomy of the Balearic landscape, human activities may have triggered and accelerated such a vegetation shift by promoting new open areas which are occupied by more dryness-adapted species from the mid- to late-Holocene transition. Definitive landscape change occurred during Chalcolithic and the Bronze Age periods when stable sedentary populations were present in the Addaia region, as has also been observed in other Minorcan sequences. In conclusion, our study confirms that long-term paleoenvironmental studies, combining off-site multi-proxy analyses with archaeobotanical and archaeological data are of fundamental importance to better disentangle the forcings involved in the Holocene landscape changes and to study the resilience of the ecosystems. The comparison of our new record from Addaia with other pollen studies from the Balearic Islands highlights the resilience of mesic vegetation to climate change. This is shown by the survival of box formations to the increased aridification initiated at ca. sixth–fifth millennium cal BCE (ca. 7–6 cal kyr BP) in the Western Mediterranean which culminated at ca. fourth–third millennium cal BCE (ca. 5–4 cal kyr BP). The coupling of dryness, prehistoric human activities and fires seems to be the cause of the definitive demise/reduction of such formations and the installation of more drought-adapted evergreen taxa. In summary, the results imply that under global warming conditions box formations will tend to decrease from their refuge sites of the Balearic Islands.

Acknowledgments

Gabriel Servera-Vives was supported by the Ministry of Economy and Competitiveness of Spanish Government (Juan de La Cierva Program: FJCI-2014-22498) and the “Programa Vicenç Mut d'Incorporació de Personal R + D + I (Pla de Ciència, Tecnologia, Innovació i Emprenedoria 2013-2017) de la Vicepresidència i Conselleria d'Innovació, Recerca i Turisme del Govern de les Illes Balears i el Fons Social Europeu (PD-018-2017)”. The work of Llorenç Picornell-Gelabert has been funded by a Beatriu de Pinós postdoctoral fellowship of the Catalan Government (2014 BP-A 00216) and by the Ministry of Economy and Competitiveness of Spanish Government (Juan de La Cierva Program: IJCI-2015-24550). Arnau Garcia-Molsosa has been supported by the University of the Balearic Islands, the Ministry of Education, Culture and Sports, Spain (CEI15-09) and “la Caixa” foundation. This work is part of the knowledge transfer of the R & D project financed by the Spanish Ministry of Economy and Competitiveness: “Archipelagos: landscapes, insular prehistoric communities and connectivity strategies in the western Mediterranean. The case of the Balearic Islands during the recent prehistory (2500–123 BC) (HAR2015, 67211-P)”. The authors want also to thank the Institut Menorquí d'Estudis and the Minorca Council for its financial and administrative support, as well as the Rubió Tudurí Foundation, Mongofre World Heritage and Es Grau Natural Park (Dir. Martí Escudero). Finally, we would like to thank Ramon Julià for the sedimentological descriptions; Joan Rita, Marzia Boi, Antoni Ferrer and Damià Ramis for their

help in the fieldwork; Yannick Miras for his contribution in the laboratory work and Núria Duran for her help in statistical procedures. We are also grateful to J.S. Carrión and one anonymous reviewer for their helpful comments improving this paper.

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